The Tevatron Connection — 10th August 2004

# *Resummations at the Tevatron*

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# *Physics at the Tevatron*

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- test the SM and do precision measurements
- search for physics beyond the SM
- probe the mechanism of hadronization and confinement

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Theoretical predictions for observables can be classified into

- fixed order predictions: systematic expansion in $\alpha_s$
  - ⚠ fail in the exclusive phase space region dominated by multiple emission of soft-collinear partons
- partons showers: combine matrix-elements & Sudakov form factors
  - ⚠ difficult to estimate the accuracy (approximated matrix elements, choice of scales, subleading effects, non-perturbative cutoffs . . . )
- resummed calculations: account for effects of multiple emissions
  - ⚠ do not respect kinematics boundaries, matching is needed and, till recently, a new analytical calculation for each new observable was required

## *Resummations at the Tevatron*

Resummed calculations for the Tevatron include

- ✗ transverse momentum resummations for heavy quark distributions
- ✗ threshold resummations for heavy quark cross sections
- ✗ threshold resummations for prompt photon at fixed $p_t$
- ✗ transverse momentum resummations for vector bosons and Higgs
- ✗ resummation of soft-collinear effects in QCD jet-observables

[e. g. Banfi, Berger, Bonciani, Bozzi, Cacciari, Catani, Dokshitzer, Ellis, Eynck, Frixione, Grazzini Huston, Kidonakis, Kucs, Kulesza, Laenen, Magnea, Mangano, Marchesini, Mrenna, Nadolsky, Nason, Oderda, Olness, Olsson, Salam, Stirling, Sterman, Vogelsang, Webber, Yuan, GZ]

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Here I will focus on jet-observables (event shapes and jet-rates)

e. g. transverse thurst, out-of-plane radiation, jet masses, jet resolution parameters. . .

- ☛ allow unique investigations in QCD
- ☛ new techniques, observables and results

# Computer Expert Semi-Analytical Resummer

Despite the clear need for a resummation for many observables, resummations have always been performed “by hand”, analytically.

CAESAR is a recently developed computer code which resums global QCD final state observables at NLL accuracy in an automated way

Banfi, Salam, GZ hep-ph/0304148, hep-ph/0407286

The user just

- ✗ fixes the Born process and the number of hard jets
- ✗ defines the observable in the form of a computer routine

CAESAR tests whether the observable is in its scope, determines the input of a general master formula and provides the full resummation

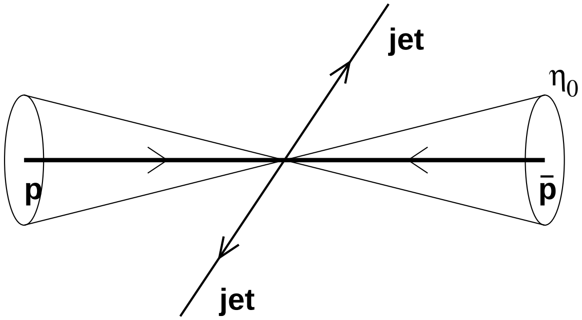
☛ straightforward resummation of a large number of observables

(as compared to painstaking, analytical studies of one observable at the time!)

# *Global observables in hadronic dijet production*

One main requirement on the observable is that it should be *global*, meaning that it should be *sensitive to emission everywhere in phase space*

⚠ *Limited experimental reach* (rapidity cut $|\eta| < \eta_0$ around the beam) conflicts with the *theoretical requirement of globalness* ⚠




Different classes observables have been designed to solve this conflict

- directly global observables

  $\Rightarrow$ measuring emissions everywhere

- indirectly global observables

  $\Rightarrow$ measure particle only in the central region, but sensitive to emissions everywhere through recoil

Banfi, Salam, GZ, hep-ph/0407287, http://qcd-caesar.org

# Comments on the observables

- the observables are designed to reconcile the theoretical need for globalness and the limited experimental reach of detectors
- observables probe QCD radiation in different regions

➥ the simultaneous study of a number of observables is a powerful tool to investigate properties of QCD radiation, e. g.

- studies of underlying event

  $\Rightarrow$ the forward sensitivity (to beam-fragmentation) can be arbitrary tuned
- studies of hadronization corrections in multi-jet events

  $\Rightarrow$ tests of power-corrections beyond the “Feynman Tube model”
- studies of non-trivial quantum evolution of colour

  $\Rightarrow$ novel perturbative QCD colour evolution structures that arise in events with 4-jet topology have never been investigated before
- tuning of Monte Carlos (e. g. use global observables!)

☛ an automated approach makes these studies feasible

# Conclusions & outlook

Resummations are crucial for the description of exclusive final-states

Significant recent progress on resummation at hadron colliders include

- a rigorous procedure to perform resummations automatically
- the definition & resummation of many new jet-observables measurable at the Tevatron and resummable with current techniques

➥ this opens up the possibility for new and challenging QCD studies

NB: some interesting observables (interjet energy flow, azimuthal decorrelation $\Delta\phi\ldots$) still beyond the scope of this automated approach

➥ encourage experimental measurements of theoretically calculable observables + widening of scope of theoretical approach.

## Requirement on the observable

- Given a Born event, when just one soft emission $k$ is radiated collinear to parton $p_\ell$, the observable should behave as

$$V(\tilde{p}, k) \simeq d_\ell \left(\frac{k_t}{Q}\right)^{a_\ell} e^{-b_\ell \eta} g_\ell(\phi)$$

(this is always the case for all observables resummed so far)

- the observable should be *continuously global*, meaning that it should be *sensitive to emission everywhere* and the *transverse momentum dependence should be uniform ($a_1 = \cdots = a_n = a$)*
- the observable should be *recursive infrared and collinear safe*, meaning that *the addition of emissions which are much softer or more collinear should not drastically change the value of the observable*

# *The master formula*

$$\boxed{\Sigma(v) =_{NLL} \sum_{\text{sub.}} \int [d\Phi]_{\text{hard}} \Sigma_s(v) \cdot \mathcal{F}(R')}$$

Banfi, Salam, GZ hep-ph/0304148 & hep-ph/0407286

✓ analytical expression for the “easy” $\Sigma_s$: *pure LL and NLL terms*

$$\Sigma_s(v) = \prod_{\ell=1}^{n_{inc}} \underbrace{f_\ell(v^{\frac{2}{a+b_\ell}} \mu_F^2)}_{\text{pdfs}} \otimes \prod_{\ell=1}^{N} \underbrace{J_\ell(L)}_{\text{jet function}} \cdot \underbrace{S\left(L/a\right)}_{\text{soft}}$$

$\Sigma_s$ can be computed in terms of simple (single-emission) properties of the observable, $a, b_\ell, d_\ell, g_\ell(\phi)$, which are determined numerically

✓ the function $\mathcal{F}$ accounts for multiple-emission effects, it is observable specific, purely NLL, since $R' = -\partial_L\{Lg_1(\alpha_s L)\} = R'(\alpha_s L)$ and can be calculated numerically

Measurements include ideally all particles, i.e. $\eta_0$ is taken as large as experimentally possible (at the Tevatron $\eta_0 \sim 3.5$)

One then defines variants of the usual $e^+e^-$ observables , e. g.

✗ Transverse thrust

$$T_T = \frac{1}{E_T} \max_{\vec{n}_T} \sum_i |\vec{p}_{ti} \cdot \vec{n}_T|$$

$\Rightarrow p_{ti}$ are the transverse momenta with respect to the Beam axis

✗ Thrust minor

$$T_m = \frac{1}{E_T} \sum_i |p_i^{out}|$$

$\Rightarrow p_i^{out}$ are the momentum-components out of the event-plane (beam axis - $n_T$-axis)

and similarly one defines jet-masses, broadenings, jet-rates . . .

☛ NLL results are valid where as long as $\log(1/v) < (a + b_{\min})\eta_0$

These observables explicitly measure only a subset of particles, but are indirectly sensitive to the remaining emissions, typically through recoil.

Select a central region $\mathcal{C}$ (e. g. $\eta_0 \sim 1$), define a central, non-global observable, e. g. a central thrust minor

$$T_{m,\mathcal{C}} \equiv \frac{1}{Q_{\perp,\mathcal{C}}} \sum_{i \in \mathcal{C}} |q_{xi}|$$

add a recoil term, e. g.

$$\mathcal{R}_{\perp,\mathcal{C}} \equiv \frac{1}{Q_{\perp,\mathcal{C}}} \left| \sum_{i \in \mathcal{C}} \vec{q}_{\perp i} \right|$$

then the recoil enhanced thrust minor is

$$T_{m,\mathcal{R}} \equiv T_{m,\mathcal{C}} + \mathcal{R}_{\perp,\mathcal{C}}$$

☛ Predictions valid as usual, but $\mathcal{F}$ diverges at some $R' = R'_c$

# Observables with exponentially suppressed forward terms

A variation of directly global observables allows to define a new class of observables with exponentially suppressed forward terms

One introduces the mean transverse-energy weighted rapidity $\eta_{\mathcal{C}}$ of a given central region

$$\eta_{\mathcal{C}} = \frac{1}{Q_{\perp,\mathcal{C}}} \sum_{i\in\mathcal{C}} \eta_i \, q_{\perp i} \qquad\qquad Q_{\perp,\mathcal{C}} = \sum_{i\in\mathcal{C}} q_{\perp i}$$

and defines an exponentially suppressed forward term

$$\mathcal{E}_{\bar{\mathcal{C}}} = \frac{1}{Q_{\perp,\mathcal{C}}} \sum_{i\notin\mathcal{C}} q_{\perp i} \, e^{-|\eta_i - \eta_{\mathcal{C}}|}$$

then e. g. the thrust minor with exponential forward suppression is

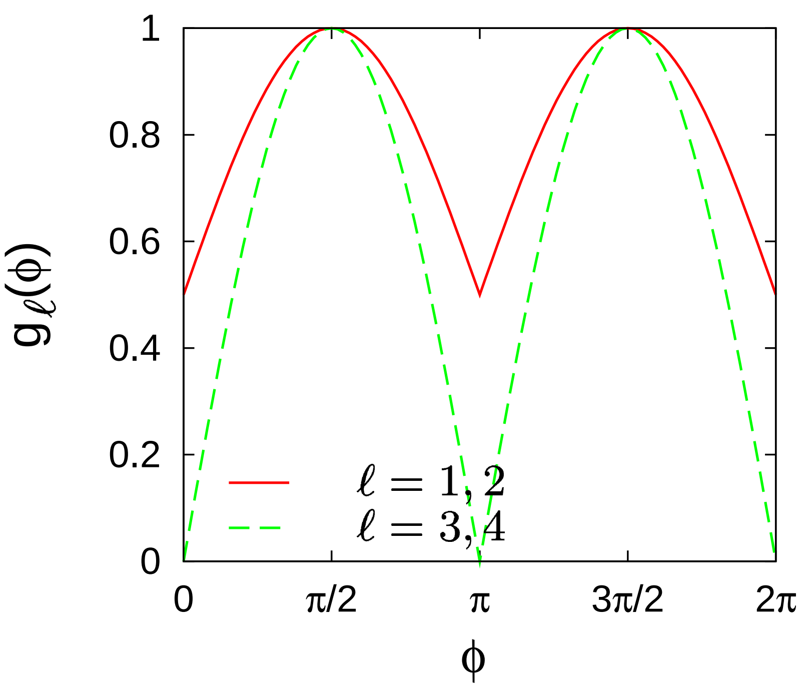
$$T_{m,\mathcal{E}} = T_{m,\mathcal{C}} + \mathcal{E}_{\bar{\mathcal{C}}} \quad \text{with} \quad T_{m,\mathcal{C}} \equiv \frac{1}{Q_{\perp,\mathcal{C}}} \sum_{i\in\mathcal{C}} |q_{xi}|$$

☛ No need for fine resolution in rapidity and azimuth in the forward region!

# Sample output: the thrust minor with recoil term

## ✗ Tests on the observable

| test | result |
|---|---|
| observable positive | T |
| global | T |
| continuously global | T |
| r-IRC safe | T |
| additive | F |

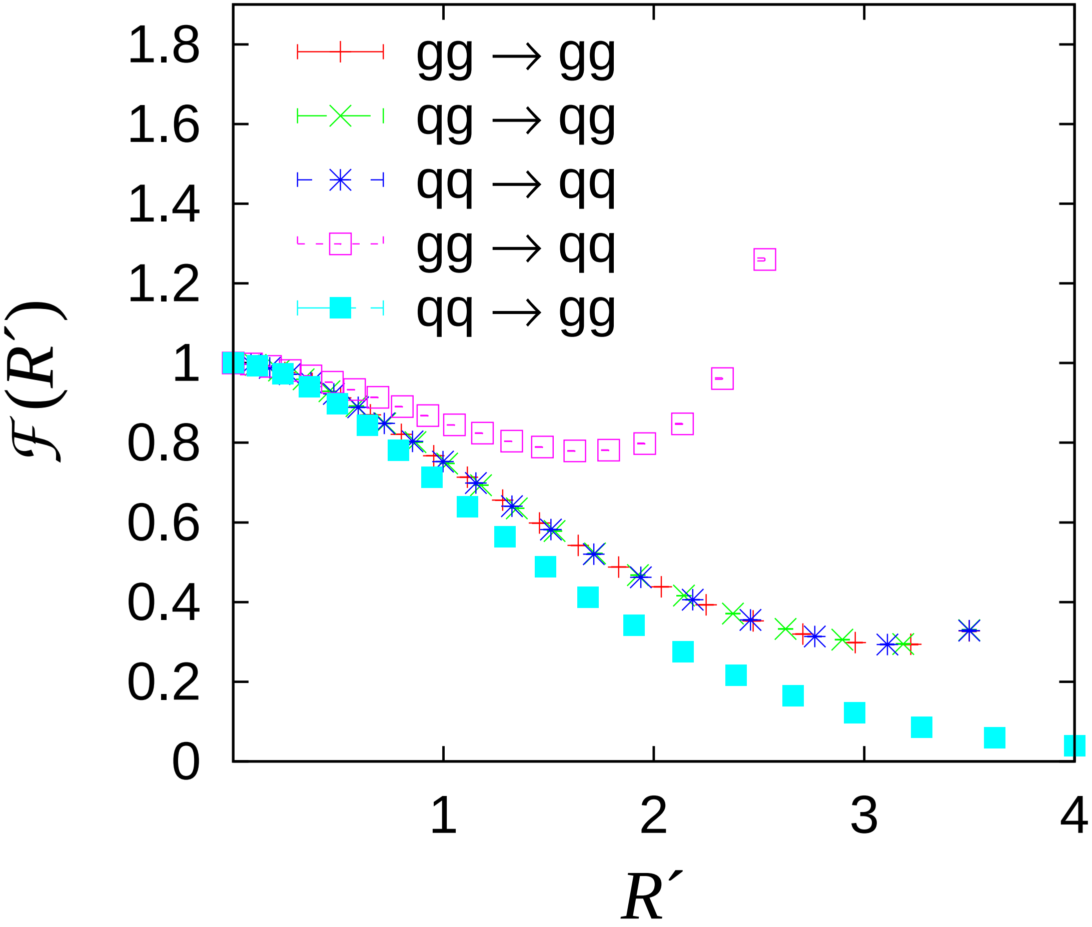



## ✗ Single emission properties

| leg $\ell$ | $a_\ell$ | $b_\ell$ | $g_\ell(\phi)$ | $d_\ell$ | $\langle \ln g_\ell(\phi) \rangle$ |
|---|---|---|---|---|---|
| 1 | 1.000 | 0.000 | tabulated | 2.000 | -0.220 |
| 2 | 1.000 | 0.000 | tabulated | 2.000 | -0.220 |
| 3 | 1.000 | 0.000 | $\lvert\sin(\phi)\rvert$ | 2.000 | -Ln(2) |
| 4 | 1.000 | 0.000 | $\lvert\sin(\phi)\rvert$ | 2.000 | -Ln(2) |

☛ Tables and plots generated automatically by CAESAR

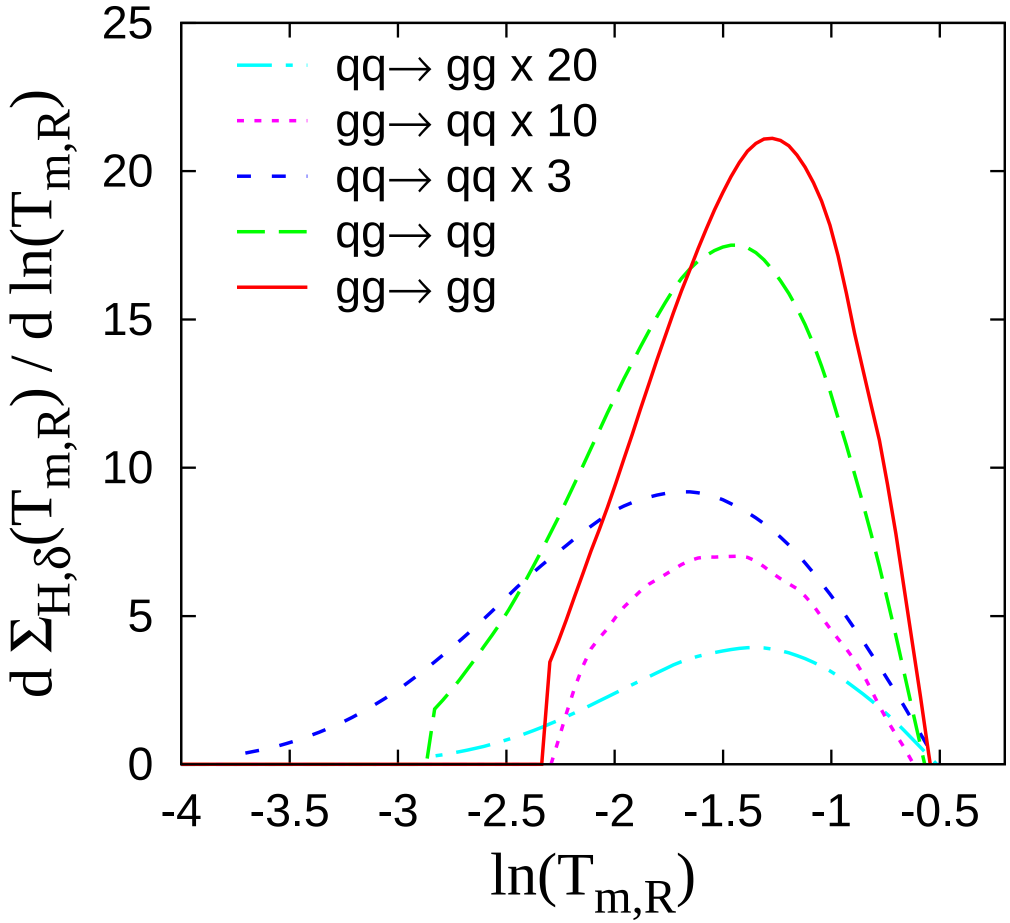
# The multiple emission function $\mathcal{F}(R')$




- strong dependence on the colour configurations
- divergence at some finite $R'$

# *The thrust minor with recoil*

Consider dijets events at Tevatron run II regime $\sqrt{s} = 1.96$ TeV with the following event selection: require 2 jets in the central region $|\eta| < 0.7$ and $E_T > 50$GeV. Measure particles around the jets $|\eta_i| < 1.1$




$\alpha_s(M_Z) = 0.118$

$\mu_F = \mu_R = P_{T,1} + P_{T_2}$

PDFS: CTEQ6M